Behaviour of long structures in response to tunnelling.

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Abstract

This paper presents observations of the response of long structures when exposed to tunnelling activities in London Clay. The type of structures varied from a 100 years old masonry arch tunnel to a more modern reinforced concrete frame structure. The common property shared by these structures was that they were long in comparison to the depth beneath them of the tunnels being constructed. Numerical analyses have also been carried out to back analyse the observed data using the London Clay soil parameters. The model was then extended to include a depth and a structural stiffness variable and demonstrate sensitivity to those factors.

Keywords
Tunnelling, structures, risk, prediction, settlement, trough, modification

Conference Theme
The effect of building stiffness

1 Introduction

The current increase in tunnelling activity in built-up areas results in an increase exposure of existing services and structures to ground movements. To assess the associated risks requires either the application of an over-simplified and conservative method or complex numerical analysis, which can be time consuming. When only the risks to the structure are of interest, the important parameter is the half-width of the settlement trough between the points of inflexion, *i*. That value is used, in conjunction with the anticipated volume loss, to produce a deflected shape for which the structure can be assessed. This paper provides a method of obtaining this parameter for long structures within a range of stiffness (EI) values.

2 Euston Square Station

In November 1996, London Electricity plc (LE) constructed a 3m diameter tunnel under the existing Metropolitan Line at Euston Square station (Lu et. al., 1999, Samuel et. al., 1999). This tunnel was driven within London Clay to achieve a clearance of approximately 7m between the two structures (see Figure 1 for plan of crossing).

The Metropolitan Line was built in 1863 (Baker, 1885), and the section under Euston Road was a brick arch constructed using the cut and cover method. The foundations of the arch were just into London Clay and the arch was covered with about 8m of Terrace Gravel and made ground.

A site investigation was conducted and brick cores were taken from the masonry to obtain both strength and stiffness parameters. The unconfined compressive tests produced a range of strengths between 6.9 and 22 N/mm^2 and the average Young's modulus was 8500 N/mm^2.

During the LE tunnel construction, precise levelling was carried out to measure the displacements along the walls and the crown. This surveying method was accurate to 1mm and the measured data at the axis and foundation (P6 and P7 respectively) is shown in Figure 2. The predicted greenfield settlement curve, based on a value of *i* calculated as half the depth between the LE tunnel axis and the arch foundations, is also shown. The back analysis of the settlement data showed a 'best fit' Gaussian curve with the point of inflexion, *i*, equal to 1.5 times the depth between the LE tunnel axis and the arch foundation. The actual settlement curve was 3 times wider than the greenfield condition and the volume loss was 2.5% one week after construction.

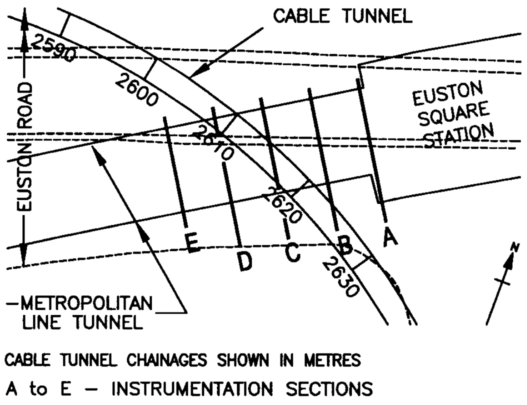

Figure 1. Plan at Euston Square Station.

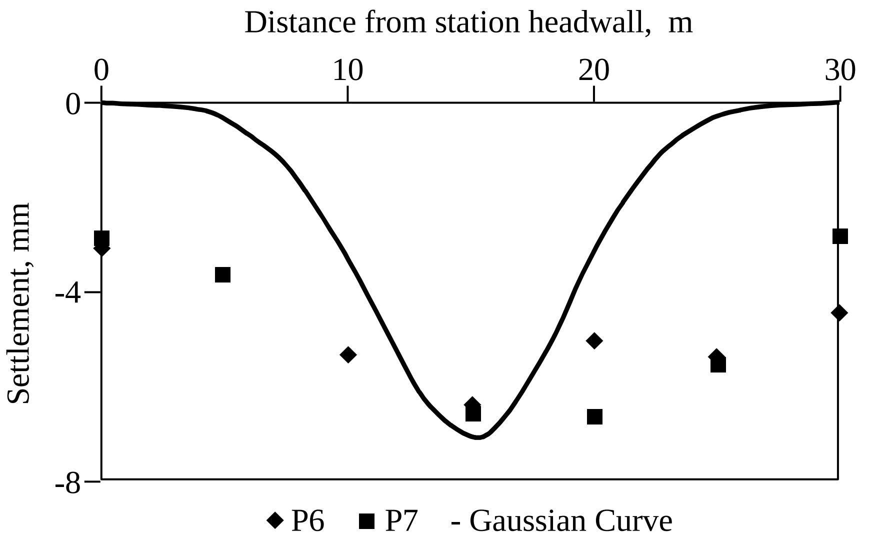

Figure 2. Observed and predicted settlements at tunnel axis and foundation levels, Euston Square Station.

3 Longford Street Spur Tunnel

A spur tunnel was excavated from an electricity substation to intersect the main tunnel drive, described in Section 2 above, at a point approximately 400m to the east of Euston Square. The spur tunnel was 77m long and 2.9m in diameter and was hand excavated in London clay on a decline at shallow depth, ranging from 4m to 15m beneath an existing structure (Bloodworth and Macklin, 1999).

The structure comprised a single-storey reinforced concrete frame which was the former basement of a substantial office development, demolished in 1996 to ground level (Figure 3). The basement extended over a wide area either side of the tunnel axis. The frame consisted of columns at 7m centres in both directions and a ground level slab. At basement level, a reinforced concrete slab was cast against the columns but was not structurally connected to them. The vertical separation of ground and basement level slabs was 4m. The columns were founded on pad footings 2m below basement slab level, approximately at the top of the London Clay. Precise level monitoring of the columns above the tunnel axis (points A – C), the basement slab over a wide area each side of the tunnel (points 1 –29) and for subsurface settlements 4m below basement slab level at a point where the tunnel axis was 8m below basement slab level (points 101 – 103) was carried out.

The settlement results at the chainage of the subsurface monitoring points are shown in Figure 4. The back analysis of the settlement data showed a volume loss of 0.8%, which was consistent with the depth of the tunnel below basement slab level and the stability number of the heading (Macklin, 1999). The trough width parameter *i* at the level of the subsurface monitoring points was found to be approximately twice the width predicted by methods based on subsurface settlement trough width in London clay (Mair et al, 1993). This widening of the trough was also observed at basement slab level.

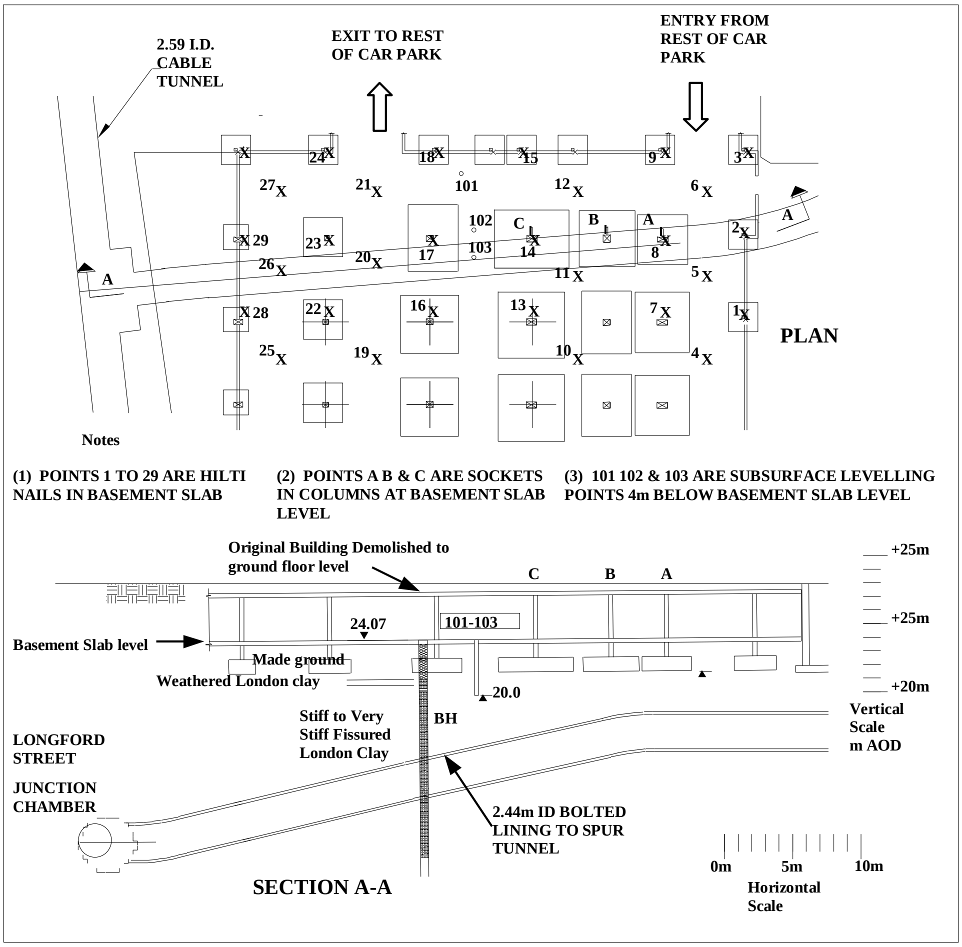

Figure 3. Plan and Section of Longford Street Spur Tunnel.

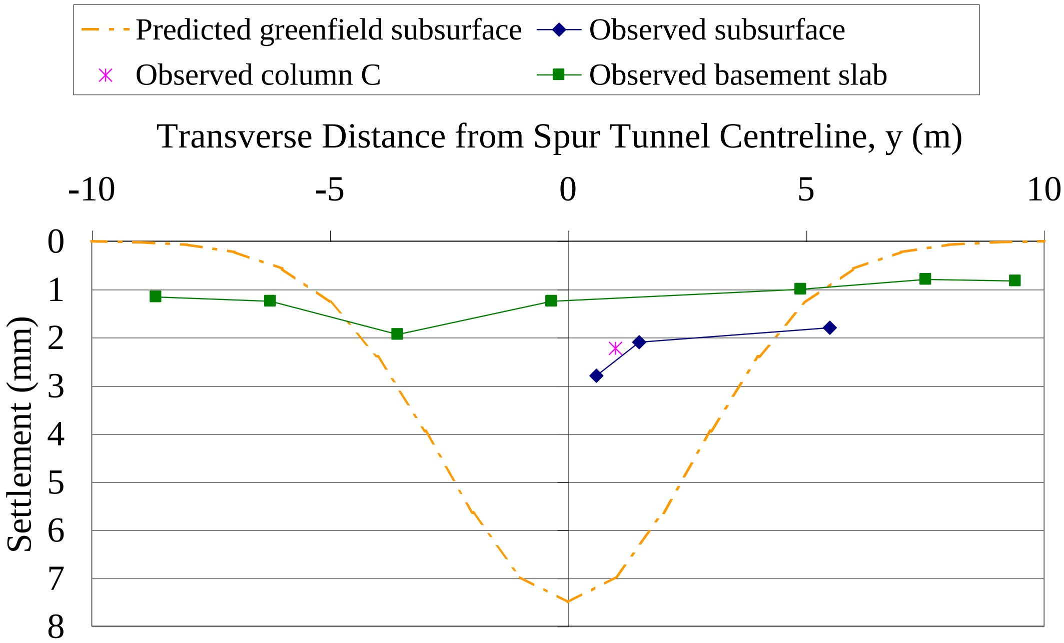

Figure 4. Predicted and observed settlement above spur tunnel, Longford St.

4 Analysis Considerations

The simplest method to assess the level of risk, due to tunnelling beneath a structure, was to assume a flexible structure with the greenfield ground displacements superimposed. From this deflected shape, the gradients along the structure were calculated and compared with published data of settlement damage to buildings (eg. Boscardin and Cording, 1989). This method yielded conservative results.

Potts and Addenbrooke (1997), proposed an alternative method, modelling the building as an elastic beam and defining relative bending and axial stiffnesses as $\rho* = EI/E_sH^4$ and $\alpha*= EA/E_sH$ respectively, where E_s was defined as the representative soil stiffness. When H, the half width of the beam, became infinitely long, both stiffnesses would reduce to very small values. In their Figure 6, the *i*/Z value then became 0.5 for all values of relative axial stiffness ratios and Z was defined as the depth between the structure foundation to the axis of the tunnel.

Based on the two cases presented, the contribution from the structure appeared to become significant when the clearance between the structure and the tunnel was reduced. This could be attributed to the reduced trough width and the ability of the structure to 'bridge' across the trough. In a limiting situation, when the stiff structure could span across a sufficiently narrow trough, very little structural deflections would be anticipated which implied a large *i*/Z ratio. This assumed that the ground was capable of carrying the increased pressure at the foundation.

A series of FLAC (Fast Lagrangian Analysis of Continua) models were developed to study the behaviour of long structures subjected to underground construction, with reference to the Euston Square Station case study (Lu et al., 1999). The structure was idealised as a long beam glued to the top of the grid. A surcharge was also included to model the material above the arch tunnel. The soil was modelled as a non-linear elastic, undrained London Clay of stiffness parameters stated in Jardine et. al.(1986). An initial analysis was conducted which excluded the structure and good agreement between the numerical and theoretical curves can be seen in the Figure 7 of Lu et. al., 1999.

Three Z values were included in the analyses, namely 4.5m, 9.5m and 15m respectively. Figure 5 and Figure 6 shows the deflected shape of the structure compared with the greenfield settlement trough of *i*/Z=0.5 for tunnels at depth, Z, of 4.5m and 15m respectively.

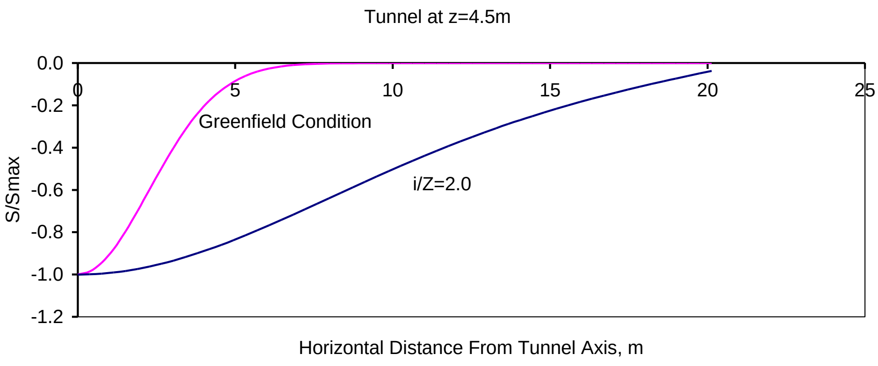

Figure 5. Deflected shape of structure for tunnel at Z=4.5m.

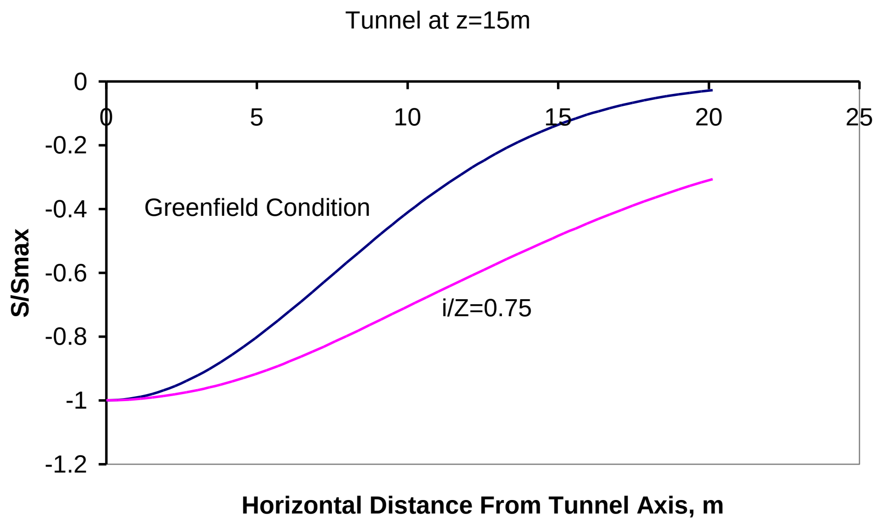

Figure 6. Deflected shape of structure for tunnel at Z=15m.

These analyses demonstrated that a reduced clearance between the tunnel and the structure would increase the trough width parameter, *i*/Z. The effect of the long structure would no longer be significant when the 3m diameter tunnel was more than 20m beneath it.

5 Proposed Design Chart and Analysis Method

A sensitivity study has been conducted to investigate the influence of the structural stiffness, EI, towards its deflected shape, where I was the gross section modulus. It was found that changing the EI from brick masonry to reinforced concrete would not have increased the trough width. The range of EI used in this work was between $1x10^7$ and $1x10^8$ kNm^2/m. Figure 7 shows the semi-log plot for the *i*/Z to C/D ratios, where C was the clear space between the tunnel and structure. Data points in the figure also include the two case studies, Euston Square station and Longford Street.

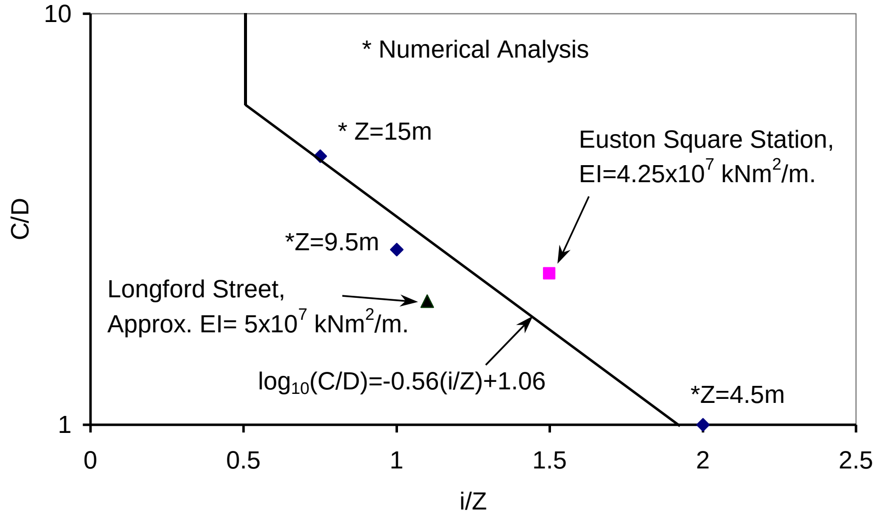

Figure 7. Proposed design chart.

The equation derived from the plot was $\log_{10}(C/D) = -0.56\,(i/Z) + 1.06$, where the i/Z ratio should not be greater than 2 or less than 0.5. This range was perceived as the upper bound based on current work and the lower bound from observed greenfield data in stiff clay. From the plot, the limiting C/D ratio, for $i/Z = 0.5$, was 6.

The recommended procedure to assess the risk on a long structure due to tunnelling would be applying the known C/D ratio to the above equation to obtain the i/Z value. This point of inflexion, i, is then combined with the anticipated volume loss to produce a deflected shape of the structure, which is compared with published structure performance charts or tables to obtain the risk levels.

6 Conclusion

Using greenfield condition to predict structure response due to tunnelling, without accounting for the structural stiffness, will provide a conservative result. However, the relative depth of the tunnel beneath the structure will also influence its deflected shape. The ability of a long structure to bridge across a settlement trough will need to be taken into consideration in order to provide a realistic prediction of the structural deflections.

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